

Open Research Online

The Open University's repository of research publications
and other research outputs

Dynamical habitability of planetary systems

Journal Item

How to cite:

Dvorak, Rudolf; Pilat-Lohinger, Elke; Bois, Eric; Schwarz, Richard; Funk, Barbara; Beichman, Charles; Danchi, William; Eiroa, Carlos; Fridlund, Malcolm; Henning, Thomas; Herbst, Tom; Kaltenegger, Lisa; Lammer, Helmut; Léger, Alain; Liseau, René; Lunine, Jonathan; Paresce, Francesco; Penny, Alan; Quirrenbach, Andreas; Röttgering, Huub; Selsis, Frank; Schneider, Jean; Stam, Daphne; Tinetti, Giovanna and White, Glenn J. (2010). Dynamical habitability of planetary systems. *Astrobiology*, 10(1) pp. 33–43.

For guidance on citations see [FAQs](#).

© 2010 Mary Ann Liebert, Inc.

Version: Version of Record

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1089/ast.2009.0379>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

Dynamical Habitability of Planetary Systems

Rudolf Dvorak,¹ Elke Pilat-Lohinger,¹ Eric Bois,² Richard Schwarz,^{1,3} Barbara Funk,^{1,3} Charles Beichman,⁴ William Danchi,⁵ Carlos Eiroa,⁶ Malcolm Fridlund,⁷ Thomas Henning,⁸ Tom Herbst,⁸ Lisa Kaltenegger,⁹ Helmut Lammer,¹⁰ Alain Léger,¹¹ René Liseau,¹² Jonathan Lunine,¹³ Francesco Paresce,¹⁴ Alan Penny,¹⁵ Andreas Quirrenbach,¹⁶ Huub Röttgering,¹⁷ Frank Selsis,¹⁸ Jean Schneider,¹⁹ Daphne Stam,²⁰ Giovanna Tinetti,²¹ and Glenn J. White^{15,22}

Abstract

The problem of the stability of planetary systems, a question that concerns only multiplanetary systems that host at least two planets, is discussed. The problem of mean motion resonances is addressed prior to discussion of the dynamical structure of the more than 350 known planets. The difference with regard to our own Solar System with eight planets on low eccentricity is evident in that 60% of the known extrasolar planets have orbits with eccentricity $e > 0.2$. We theoretically highlight the studies concerning possible terrestrial planets in systems with a Jupiter-like planet. We emphasize that an orbit of a particular nature only will keep a planet within the habitable zone around a host star with respect to the semimajor axis and its eccentricity. In addition, some results are given for individual systems (*e.g.*, Gl777A) with regard to the stability of orbits within habitable zones. We also review what is known about the orbits of planets in double-star systems around only one component (*e.g.*, gamma Cephei) and around both stars (*e.g.*, eclipsing binaries). Key Words: Orbital dynamics—Habitability—Terrestrial exoplanets. *Astrobiology* 10, 33–43.

1. Relevance of Orbital Dynamics to Planetary Habitability

WHETHER A BIOSPHERE can develop on a terrestrial planet that has formed in the habitable zone (HZ)¹ or possibly migrated into this “favorable region” of its host star

depends, in part, on its dynamical evolution in the planetary system within which other planets may be present as well. The environmental circumstances on such a planet may change rapidly, however, when elements of the orbit undergo significant changes, and life may be prevented from evolving.

With regard to stability, the “ideal planetary system” would consist of only two spherical bodies: a star and a

¹For a definition of the HZ we refer to the work of Kasting *et al.* (1993).

¹Institute for Astronomy, University of Vienna, Vienna, Austria.

²Observatoire de la Côte d’Azur, Nice, France.

³Department of Astronomy, University of Budapest, Budapest, Hungary.

⁴NASA Exoplanet Science Institute, California Institute of Technology and Jet Propulsion Laboratory, Pasadena, California, USA.

⁵NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

⁶Universidad Autonoma de Madrid, Madrid, Spain.

⁷Research and Scientific Support Department, ESA, European Space Research and Technology Centre, Noordwijk, the Netherlands.

⁸Max-Planck Institut für Astronomie, Heidelberg, Germany.

⁹Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA.

¹⁰Space Research Institute, Austrian Academy of Sciences, Graz, Austria.

¹¹Université Paris-Sud, Orsay, France.

¹²Department of Radio and Space Science, Chalmers University of Technology, Onsala, Sweden.

¹³Lunar and Planetary Laboratory, Tucson, Arizona, USA.

¹⁴Istituto Nazionale di Astrofisica, Rome, Italy.

¹⁵Space Science & Technology Department, CCLRC Rutherford Appleton Laboratory, Oxfordshire, UK.

¹⁶Landessternwarte, Heidelberg, Germany.

¹⁷Leiden Observatory, Leiden, the Netherlands.

¹⁸University of Bordeaux 1, Bordeaux, France.

¹⁹Observatoire de Paris-Meudon, Laboratoire de l’Univers et ses Théories, Meudon, France.

²⁰SRON, Netherlands Institute for Space Research, Utrecht, the Netherlands.

²¹Department of Physics and Astronomy, University College London, London, UK.

²²The Open University, Milton Keynes, UK.

planet. In a two-body system with two spherical bodies, a star and a planet, the orbit would follow a perfectly stable, periodic Keplerian orbit. In a multiplanet system in which the gravitational interaction between the planets themselves can be neglected because the other planets have small masses and are significantly distant from each other, it can be assumed that every planet will form a two-body system with the star. Consequently, each planet would thus be expected to follow a stable Keplerian orbit or a good approximation thereof. In cases where the mutual interaction between planets cannot be neglected, the planetary system should be considered to be an n -body problem (with $n > 2$).

The pioneering work of Poincaré at the end of the 19th century has shown that, in the n -body case, orbits are mainly irregular, and the planetary system is likely to be chaotic. The planets in the Solar System do interact gravitationally with each other. Earth, for example, is in particular disturbed by the massive planet Jupiter and suffers even from being in a 13:7 resonance of the mean motions with the planet Venus. The perturbations are, however, too small to change orbits drastically within timescales of billions of years (see, *e.g.*, Laskar, 1990, 1998; Laskar *et al.*, 1992), which is long enough for life to develop and evolve. In the following sections, we investigate various scenarios of planetary configurations of exosolar systems and their relevance to the dynamic evolution of terrestrial exoplanets.

2. Theoretical Techniques for Studying the Dynamics of Multiplanetary Systems

The dynamics of exoplanetary systems (EPS) with more than one planet, including close-in gas giants, is clearly dominated by nonlinear interaction; therefore, chaotic behavior would be expected in these cases. Generally, for multiplanetary Upsilon Andromedae-type systems, the stability of the system, as well as its life span, strongly depends on the hierarchical distribution of the planetary masses and their relative inclinations (*e.g.*, Kiseleva-Eggleton and Bois, 2001).

In most multiplanetary systems, however, the strong dynamical interactions between planets lead to planetary orbital parameters—if standard two-body Keplerian fits are applied—that are imprecise (Laughlin and Chambers, 2001, 2002). Furthermore, an uncertainty also exists in the determination of planetary masses. Therefore, the available parameter space must be explored to exclude initial conditions, which may lead to dynamically unstable configurations (*e.g.*, Ferraz-Mello *et al.*, 2005). For a recent review on the dynamics of EPS see Michtchenko *et al.* (2008).

To study this highly nonlinear dynamics with a great number of degrees of freedom, workers will need to adapt classical methods of global analysis but also develop new techniques that allow for location of the stable and unstable trajectories simultaneously with a wide range of the orbital parameters. They will also need to quantify the degree of instability and distinguish regular from chaotic behaviors.

A classical technique, the method of Lyapunov characteristic numbers, allows for distinguishing between regular and chaotic dynamical states. This method requires computations over long evolutionary times, sometimes much longer than the lifetime of the studied system. Numerical methods

that converge faster and more sensitively than the Lyapunov characteristic numbers technique are required to prove relevant information about the global dynamics and the fine structure of the phase-space. Such methods should simultaneously yield a good estimate of the Lyapunov characteristic numbers but with a comparatively small computational effort. One such method is the mean exponential growth factor of nearby orbits (MEGNO) method (Cincotta *et al.*, 2003), which can be successfully applied to the study of several known exoplanetary systems (*e.g.*, Goździewski *et al.*, 2001; Kiseleva-Eggleton *et al.*, 2002a, 2002b, 2003). Also, Froeschlé *et al.* (1997) and studies like that of Pilat-Lohinger *et al.* (2003) applied the fast Lyapunov indicator for several orbital dynamical studies.

3. Orbital Stability in Multiplanetary Systems

A planetary system with multiple planets can be stable if planetary orbits are close to stable resonant periodic orbits. It has been recently confirmed that, in 4 of 33 known multiplanetary systems, two planets are locked in 2:1 mean motion resonance (MMR). One such system displays 3:1 MMR (55 Cnc); and, in another, the period ratio is close to 7:3 (47 Uma).

- Two orbits are said to be in MMR if the ratio of their periods can be expressed as the ratio of two small integers, for example, 1:1, 2:1, 3:1, 3:2.

It seems that all planets with highly eccentric orbits belong to resonant systems. A $p:q$ MMR means that the orbital period of the outer planet is $p:q$ times that of the inner planet. A study by Hadjidemetriou (2002) of periodic orbits in 2:1 MMR predicted stable and unstable configurations of multiplanetary systems, depending on the hierarchy of planetary masses and eccentricities. For instance, according to this study, in the planetary system Gliese 876 the mass $M_b < M_c$ and the eccentricity $e_b > e_c$ are in a stable configuration. Lee and Peale (2002) studied the 2:1 MMR orbital resonances of the Gliese 876 planets, following the orbital fit obtained by Laughlin and Chambers (2001).

The stability of the Gliese 876 resonance configuration for values of the inner planet's eccentricity of up to 0.86 was a surprise. For multiplanetary systems of Gliese 876 type, where two giant planets are locked in MMR, it can be shown that a global analysis in the parameter space is able to identify the exact location of the 2:1 MMR and its width (Goździewski *et al.*, 2002). Bois *et al.* (2003) showed that, for an anti-aligned configuration, the robustness of the orbital stability is given by the width of the resonance zone in the a_b , a_c parameter space and by the stability valley, as presented in Fig. 1a, 1b.

It should be understood that MMR, coupled with an adequate relative spacing of the planets on their orbits, would avoid close approaches between planets, for instance, at their periastron. This leads to a requirement of an additional stability mechanism, the so called apsidal secular resonance (ASR), which is a synchronous precession between the two orbital planes. There are two types of ASR: aligned and anti-aligned.

- Either type of ASR can be stabilizing or destructive. It appears that both types are present in currently

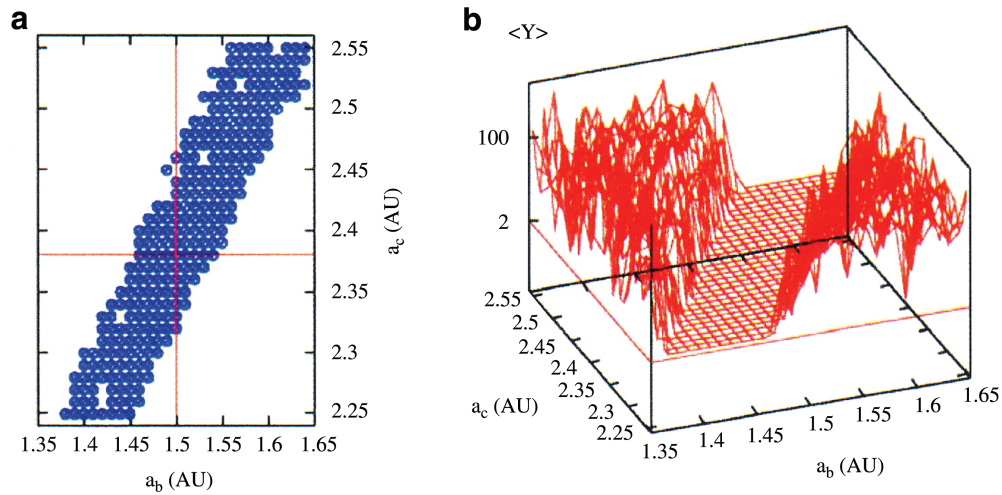


FIG. 1. (a) Cross section of (b) in the plane $\langle Y \rangle = 2$; the stability strip in (a) corresponds to the stability valley in (b). The semimajor axes a_b and a_c have to follow particular rates corresponding to the 2:1 resonance in mean motions (two revolutions of the inner planet and one of the outer planet during the same period of time). Stability maps in the a_b, a_c parameter space are taken from Bois *et al.* (2003). a_b and a_c are the two semimajor axes of the planets b and c of an anti-aligned system. (b) The 3-D plot shows the existence of a stability valley surrounded with peaks of strong instabilities (the peaks indicate the magnitude of instabilities). $\langle Y \rangle$ is the MEGNO indicator characteristic value (Cincotta and Simó, 2000). Color images available online at www.liebertonline.com/ast.

discovered exoplanetary systems. Apsidal resonances have been found in systems with and without lower-order (2:1, 3:1) MMR.

This stabilizing mechanism could be the key to the existence of a class of planetary systems in which giant planets are very close to each other coupled to a 2:1 orbital resonance (Bois *et al.*, 2003), as shown in Fig. 1a, 1b. The stabilizing mechanisms could determine the dynamical behavior of exosolar systems, such that their planets are never too close to each other (various relative inclinations between the two orbits are also considered). The whole stability mechanism allows for the avoidance of close approaches between planets, especially at their periapease (Zhou and Sun, 2003).

The HD82943 and HD12661 systems are the first two found in anti-aligned apsidal resonance (Ji *et al.*, 2003; Lee and Peale, 2003). However, HD82943 is a very interesting system that shows a similar stable resonance zone in the a_b, a_c parameter space for both possibilities—aligned and anti-aligned.

There are indications that planetary orbits in almost all multiplanetary systems are locked in ASR, so that combined studies of both types of resonances (MMR and ASR) are essential for finding solutions to planetary stability problems (*e.g.*, Chiang and Murray, 2002; Lee and Peale, 2002). The problem of the capture of planets into resonant configurations during their early evolution is becoming a main objective for future research programs. Recent studies have shown that planetary capture into MMR is related to the properties of the disk and the planetary parameters (*e.g.*, Kley *et al.*, 2004).

Recently, an interesting idea has shown the possible existence—at least from the dynamical point of view—of planets in stable retrograde orbits in MMR (Gayon and Bois, 2008). Although it seems to be a very peculiar case of the mechanism of formation of planetary systems, we cannot exclude the existence of such exotic EPS because it was also

not expected that high eccentric planetary orbits with $e > 0.8$ exist.

4. The Current Knowledge of the Structure of Exoplanetary Systems

To date, almost 350 planets have been detected and confirmed to move in exoplanetary systems, and it is evident that they are very different compared to the Solar System. This is clear from Figs. 2 and 3, which show the mass distribution of the discovered planets.

- 34% of the detected planets have masses $< M_{\text{Jup}}$, and 9% have masses $< 0.1 M_{\text{Jup}}$.

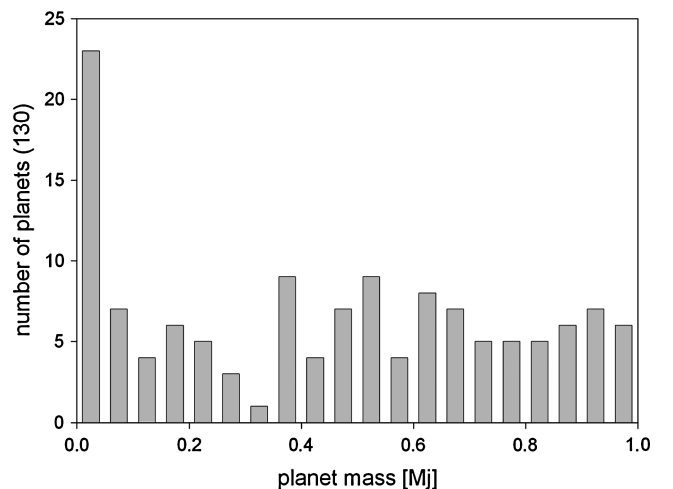


FIG. 2. Histogram of exoplanets up to $1 M_{\text{Jup}}$. The number of planets in this region is 130. Data taken from J. Schneider (<http://exoplanet.eu>).

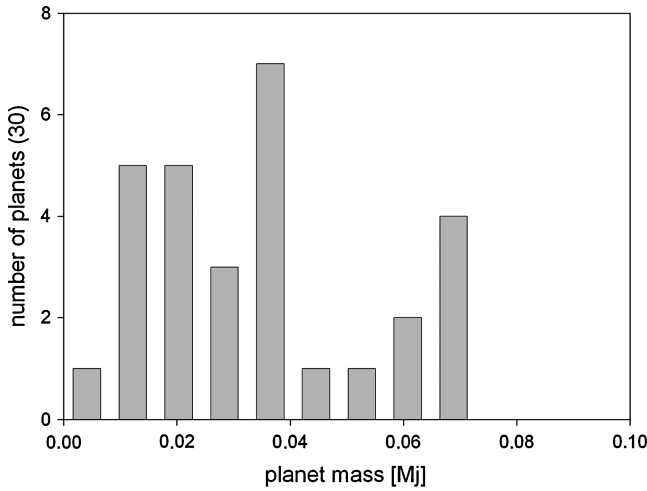


FIG. 3. Histogram of exoplanets up to $0.1 M_{\text{Jup}}$. The number of planets in this region is 30. Data taken from J. Schneider (<http://exoplanet.eu>).

None of the planets observed in EPS are of Earth mass, though, with the European satellite CoRoT (Barge *et al.*, 2008), a “super-Earth” ($<11 M_{\text{Earth}}$) has recently been found to move around a K0V star. Because of the small distance to its host star (semimajor axis $a=0.18$ AU, period $P=0.82$ days), the planet is far too hot to be habitable; the estimated temperature is more than 1000 degrees! In fact, most of the exoplanets are in close-by orbits to their stars, which is most certainly a biased value, given that we have only observed them over the course of about 15 years with techniques that favor the detection of such planets with small orbital periods.

- About 15% of the planets are closer to their host stars than Mercury is to the Sun.

In Figs. 4, 5, 6, and 7, we have plotted the distances (semimajor axes) of discovered planets to their stars for

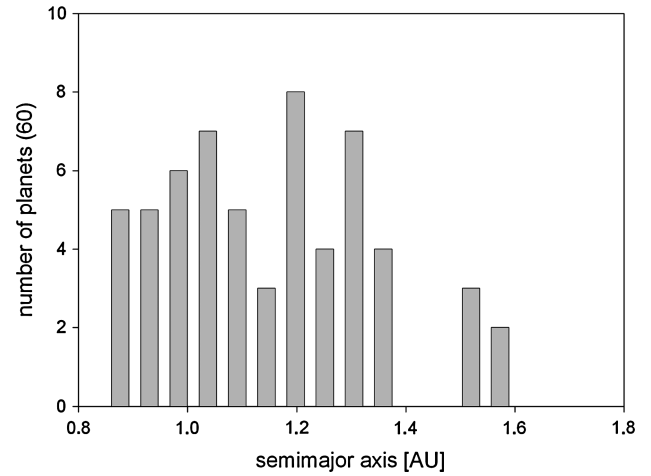


FIG. 5. Histogram of exoplanets in the HZ of a G star. The number of planets in this region is 60. Data taken from J. Schneider (<http://exoplanet.eu>).

known planetary systems of the four spectral types F, G, K, and M. The most surprising finding for astronomers was that the eccentricities of the orbits were large (Fig. 8):

- Nearly 60% of the planets have eccentricities >0.2 (Mercury), and even 40% have eccentricities >0.3 .

We can conclude that none of the planets are Earth-like and have all the necessary properties to develop a biosphere. What is crucial with regard to future studies, however, is the possibility for additional Earth-like planets orbiting a host star such that, at least theoretically, life as we know it could develop at its surface. Dvorak (2008) devoted several chapters to dynamical stability and habitability with regard to exoplanets (Kaltenegger and Selsis, 2007; Beaugé *et al.*, 2008; Dvorak and Pilat-Lohinger, 2008; Lammer *et al.*, 2008; Michtchenko *et al.*, 2008; Pilat-Lohinger and Dvorak, 2008; von Bloh *et al.*, 2008).

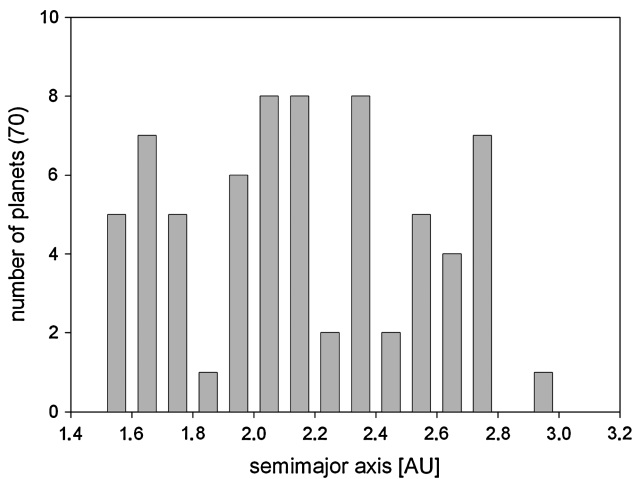


FIG. 4. Histogram of exoplanets in the HZ of an F star. The number of planets in this region is 70. Data taken from J. Schneider (<http://exoplanet.eu>).

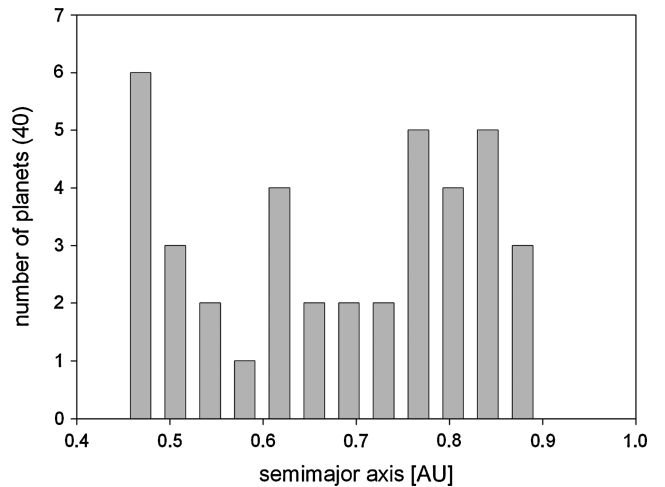


FIG. 6. Histogram of exoplanets in the HZ of a K star. The number of planets in this region is 40. Data taken from J. Schneider (<http://exoplanet.eu>).

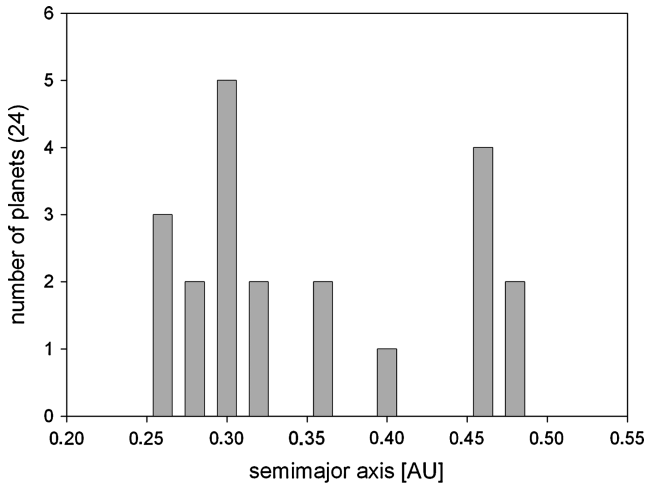


FIG. 7. Histogram of exoplanets in the HZ of an M star. The number of planets in this region is 24. Data taken from J. Schneider (<http://exoplanet.eu>).

5. EPS with Giant Planets and Terrestrial Planets in the HZ

Regarding the dynamics of the orbits of giant planets and HZs in EPS, the following classes can be distinguished (see Fig. 9):

- C1: a Jupiter-like planet with an orbit very close to the host star (= a hot Jupiter) such that outside stable orbits could occur for timescales long enough for a biosphere to develop.
- C2: a Jupiter-like planet that moves to great distances away from the central star, a “cold” Jupiter; stable low eccentric orbits for additional planets may exist at shorter distances from the star.
- C3: a Jupiter-like planet that moves within the HZ; terrestrial-like satellites (like, *e.g.*, Titan in the system of Saturn) could be on stable orbits.

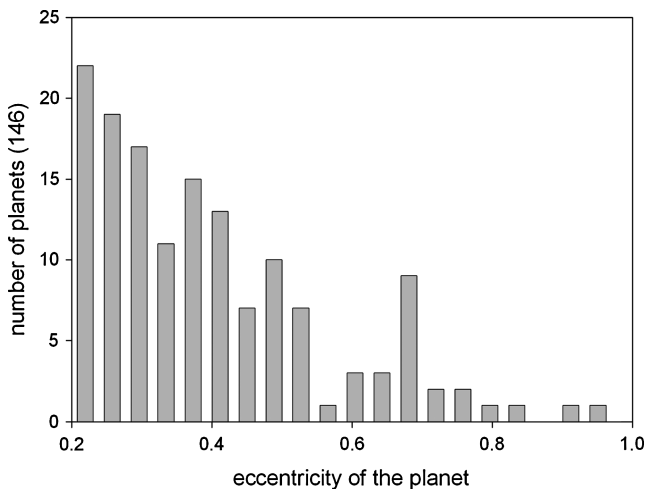


FIG. 8. Histogram of exoplanets for eccentricities between 0.2 and 0.4. The number of planets in this region is 146. Data taken from J. Schneider (<http://exoplanet.eu>).

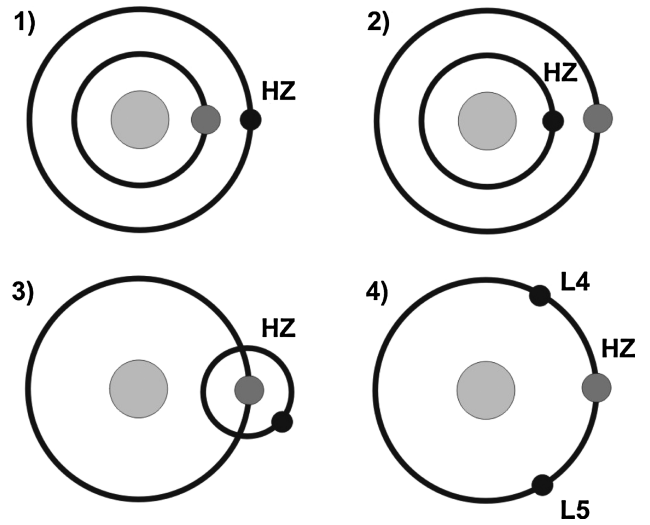


FIG. 9. Schematic figure for the different possibilities where we may find additional, habitable planets in existing exoplanetary systems. For a detailed description of the groups (1–4, C1–C4), we refer to section 5.

- C4: a Jupiter-like planet inside the HZ that allows, under certain conditions, for a Trojan-like terrestrial planet that may move on a stable orbit around one of the Lagrangian equilibrium points L_4 or L_5 . These points always form an equilateral triangle with the host star and the planet.

There is no need for further dynamical investigation of the C1 group because the very close giant planet would hardly perturb a terrestrial planet in the HZ. The C2 group has been studied carefully because sometimes the gas giants have large eccentricities that do not allow stable orbits in the HZ. Many investigations (*e.g.*, Menou and Tabachnik, 2003; Raymond *et al.*, 2004, 2006; Raymond and Barnes, 2005; Raymond, 2006) have been devoted to this configuration.

In Fig.10, we show the maximum eccentricity of the Earth for different semimajor axes and eccentricities of Jupiter. According to these results, the perturbing Jupiter can be quite close to the HZ in case of low eccentric motion.

An extensive numerical investigation of fictitious bodies in the dynamical model of the elliptic restricted three-body problem has been accomplished by Sándor *et al.* (2007). With the aid of these results (see Fig. 11), a first estimate can be made as to whether planets are dynamically stable. For details with regard to this so-called “Exocatalogue,” we refer the reader to the home page: <http://www.univie.ac.at/adg>.

For the C3 group, the limit of a terrestrial satellite orbiting a giant planet in the HZ is estimated analytically via the Hill radius, which is a rough estimate of the sphere of influence of a planet.

The C4 group is interesting because these are orbits of hypothetical terrestrial planets with a “Jupiter” in 1:1 resonance; these could be termed Trojan planets (in reference to the group of the Trojan asteroids in the Sun-Jupiter system that always move close to 60 degrees ahead and 60 degrees behind Jupiter). These orbits have two different periods of

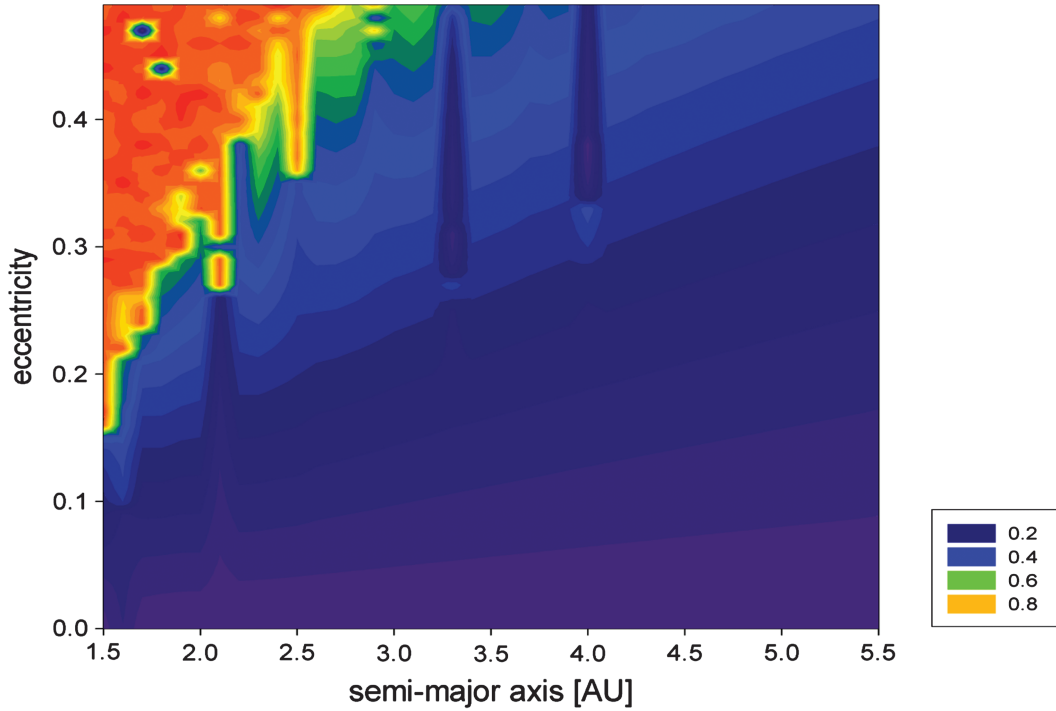


FIG. 10. A stability map for an Earth-like planet in the $a_{\text{Jup}}, e_{\text{Jup}}$ parameter space for the Sun-Jupiter system. Stable motion of the terrestrial planet for a long time span is given by the blue area, while the red area labels the chaotic motion. The position of Jupiter was varied from 1.5–5.5 AU, and its eccentricity was increased from 0–0.5.

librations around their equilibrium points, which depends on the mass ratio of the primaries (for details see Schwarz *et al.*, 2007). For terrestrial Trojan planets, the results of numerical integration can be used for a whole grid of initial conditions around the point L_4 (L_5). Two different models, depending on the eccentricity e of the primaries' orbit ($e=0$ and $e=0.05$), show the extension of the stable region, depending on the mass ratio “Jupiter”/host star (z -axes) (Figs. 12 and 13). The largeness with respect to the semimajor axis (y -axes) is plotted versus the angular distance to the Lagrange point itself, which is located at 60 degrees. Globally, it could be said that an eccentricity $e < 0.3$ leads to stable orbits of planets of class C4;

this value is also a kind of limit for staying in the HZ long enough to guarantee a climate that would allow for moderate temperatures and avoid prolonged time intervals in regions where it is too hot or too cold.

For a planet to be considered a terrestrial planet, several constraints in physical composition must be taken into account; this is explained in other chapters in this volume. In addition to orbital parameters, the semimajor axis, and the eccentricity, it is essential to know the size and the mass of a planet. Thus, the long runs of light-curve observations of transiting planets, along with the respective radial velocity measurements, allow for complete characterization of the

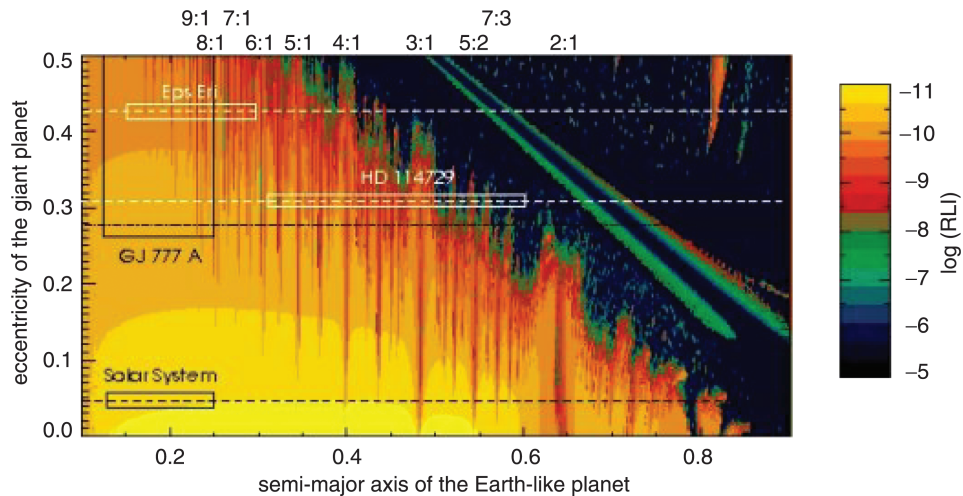


FIG. 11. Stability map from the Exocatalogue (<http://www.univie.ac.at/adg>).

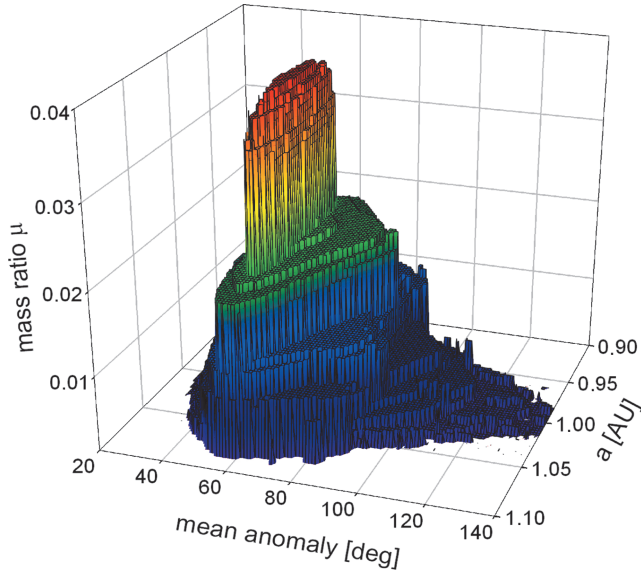


FIG. 12. The stability area around the Lagrangian equilibrium point L_4 (semimajor axis versus mean anomaly) for $e=0$ depending on the mass ratio μ .

planet's orbital parameters when the planet passes in front of its host star. This kind of snapshot, compared to the dynamical and physical lifetime of a planetary system, should provide, together with the determined astrophysical data of the host star, the mass and density. In addition, the determined orbit allows for an understanding of the variation of light flux of the host star on the planet's surface, because knowing the period and the masses involved, and the semimajor axis of its orbit together with the eccentricity, allows for the gathering of information about the possible habitability of the planet. Large eccentricities ($e > 0.3$) lead to a rather short residence in hotter regions around the star, whereas the planet stays primarily in the colder region. As

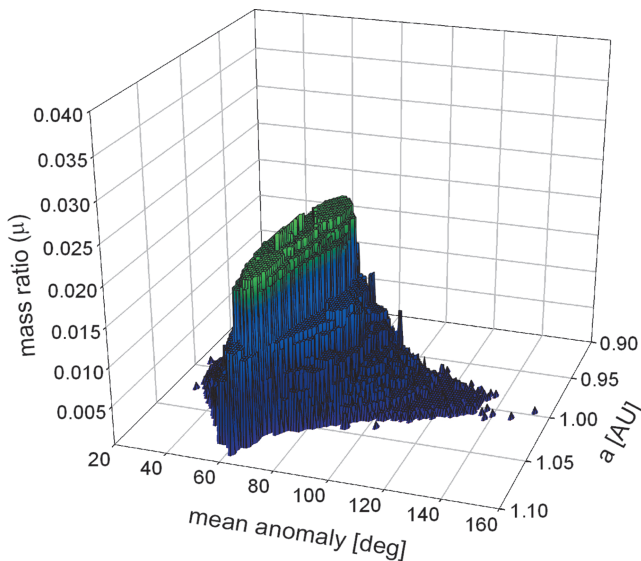


FIG. 13. The stability area around the Lagrangian equilibrium point L_4 (semimajor axis versus mean anomaly) for $e=0.05$ (Jupiter case) depending on the mass ratio μ .

TABLE 1. INFLUENCE OF ECCENTRICITY e ON EARTH-ANALOG PLANETS WITHIN THE HZ

e_{planet}	Hot zone	HZ	Cold zone
0.0	0	365	0
0.1	0	365	0
0.2	105	121	139
0.3	113	79	173
0.4	111	59	195
0.5	105	47	213
0.6	97	39	229
0.7	88	34	243
0.8	79	29	257
0.9	69	26	270

an example, an Earth-analog planet orbiting a Sun-like star in 1 AU and with an eccentricity of $e=0.3$ would reside only 79 days in the HZ but 113 days in the hot zone and 175 days in the cold zone (see Table 1). Thus, it is evident that, the semimajor axis aside, eccentricity is a crucial orbital parameter when assessing whether a planet is habitable.

6. Results for Known Exoplanetary Systems

Research groups have put considerable effort into finding stable solutions for orbits of hypothetical terrestrial planets in observed exosolar systems. By applying the various techniques and methods discussed above, stable planetary orbits with reasonable eccentricities in the HZ of their host stars can be immediately ruled out for some of the known exosolar systems. For other exosolar systems, there is good potential for the occurrence of long-time dynamically stable orbits. We have already mentioned that the MEGNO and the fast Lyapunov indicator are stability indicators. Another rather simple check is to consider the value of the maximum value of the orbital eccentricity, which has turned out to be a very efficient stability indicator (e.g., Dvorak *et al.*, 2003). A good measure for such cases was introduced by Menou and Tabachnik (2003), who defined the zone of influence from $[R_{\text{in}} + (1 - e)a - R_H]$ to $[R_{\text{out}} + (1 + e)a - R_H]$, where R_H is the Hill radius, which depends on the semimajor axis of the orbit of the giant planet and its mass compared to the mass of the host star.

Menou and Tabachnik (2003) studied the orbital stability of a potential terrestrial planet within the HZ for 85 of the known exoplanetary systems around single stars. For each system, they seeded the HZ with 100 randomly distributed terrestrial planets. The number of remaining terrestrial planets after an integration time of 1 million years is taken as a measure of the dynamical habitability of the system. For these 85 systems they found that:

- About 25% retained a high percentage (60% to 80%) of the terrestrial planets in their HZ.

Most of these systems had a close-in giant planet on a nearly circular orbit.

- Another 25% retained a small but finite number of the terrestrial planets in their HZ.

The planets that survived tended to be located in the middle of the HZ, if this zone did not overlap with the orbit of the giant

planet. If the giant planet entered the HZ, the terrestrial planets on the opposite side of the zone survived.

- The remaining 50% lost their terrestrial planets in the HZ due to the strong perturbations of a giant planet.

Menou and Tabachnik (2003), it appears, underestimated the role of resonances. Asghari *et al.* (2004) undertook a thorough dynamical investigation of 5 exoplanetary systems by using extensive numerical experiments and taking into account the mean motion resonances between hypothetical terrestrial planets and the existing gas giants in five exoplanetary systems. A fine grid of initial conditions for a potential terrestrial planet within the HZ was chosen for each system, from which the stability of orbits was then assessed by direct integrations over a time interval of 1 million years. For each of the five systems, a two-dimensional grid of initial conditions contained 80 eccentricity points for the known jovian-class planets and up to 160 semimajor axis points for the hypothetical terrestrial planet. The computations were carried out by using a Lie-series integration method with an adaptive step size control. This integration method achieved machine precision accuracy in a highly efficient and robust way and required no special adjustments when the orbits had large eccentricities.

Other studies have concentrated on the following systems: Gl777A (Naef *et al.*, 2003), HD72659 (Butler *et al.*, 2003), Gl614 (Naef *et al.*, 2004), 47Uma (Butler and Marcy, 1996) and HD4208 (Vogt *et al.*, 2002). The results of these studies can be summarized as follows:

- *Gl777A*: In this system, the stability zone for the motion of terrestrial exoplanets is well inside the HZ, and results suggest that any exoplanets residing there will survive for a sufficiently long time [in Menou and Tabachnik (2003), 86% of the orbits were found to be stable].
- *47Uma*: The simulations yield a good chance for finding terrestrial exoplanets within the HZ with small eccentricities between the main resonances [this result does not agree with Menou and Tabachnik (2003), where only 28% remained stable].
- *HD72659*: This system turned out to be a very good candidate for hosting terrestrial exoplanets within the HZ [in the study of Menou and Tabachnik (2003), only 40.2% of the orbits inside the HZ are stable].
- *Gl614*: Terrestrial exoplanets in the HZ were found to be very unlikely [this result is consistent with Menou and Tabachnik (2003), who found also that only 9.2% of the orbits are stable].
- *HD4208*: The simulation implied a reasonable change of finding terrestrial exoplanets that could survive for a sufficiently long time [this result is more or less consistent with Menou and Tabachnik (2003), that 50.2% of the orbits remained stable].

7. Terrestrial Planets in Binaries

Several studies (*e.g.*, Dvorak *et al.*, 2003; Érdi *et al.*, 2004) have shown that the constraints for terrestrial planets in binaries are more severe, due to the strong perturbations of a second star, especially when the HZ is between the two stars. High eccentric motion of the binary would not permit stable motion in the HZ.

The study of planets in binaries is very important, since we know that more than 60% of the Sun-like stars form double or multiple-star systems (at least in the solar neighborhood). From the dynamical point of view, we distinguish three types of motion in double-star systems (Dvorak, 1984):

- the satellite-type (or S-type) motion, where the planet moves around one stellar component;
- the planet-type (or P-type) motion, where the planet surrounds both stars in a very distant orbit;
- the libration-type (or L-type) motion, where the planet moves in the same orbit as the secondary but 60 degrees before or behind—furthermore, they are locked in 1:1 mean motion resonance.

Currently, the S-type motion is the most interesting one of the three, since all detected exoplanets in binary systems orbit one of the stars. The P-type motion will be more important when we have the capability to detect planets in very close binaries. In principle, we know that the planetary motion around both stars is only stable for distances (from the mass center) 2 times the distance between the two stars. In the case of high eccentric motion of the binary (around 0.7), the planet's distance has to be more than 4 times that between the two stars to be stable. [For details, see, *e.g.*, Dvorak *et al.* (1989), Holman and Wiegert (1999), Pilat-Lohinger *et al.* (2003), Pilat-Lohinger and Dvorak (2008).] L-type motion is not so interesting for planetary motion in double stars due to a limitation in the mass ratio of the two stars $m_2/(m_1+m_2) < 1/26$. This motion is more interesting for single-star-giant planet systems, where the limit of the mass ratio is easily fulfilled.

At present, we know of 44 binaries that host one or more giant planets; most of them are very distant double stars, so that the planetary motion is not influenced by the second star. There are a few systems (*e.g.*, gamma Cephei, HD41004AB, Gliese86) with a separation of the two stars around 20 AU, where stability studies are of great importance. The three binary systems represent an example for the

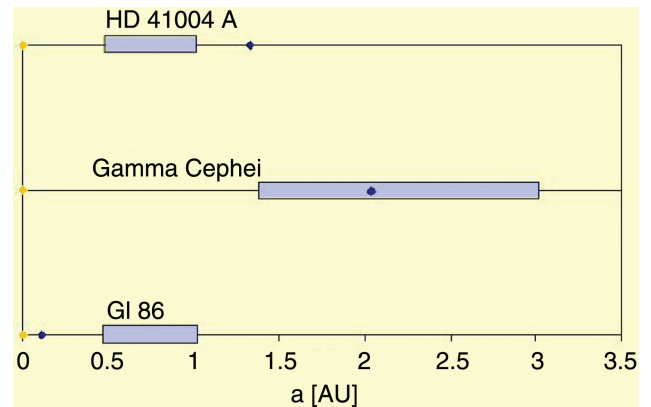


FIG. 14. The three cases concerning giant planets (blue dots) and the location of the HZs (blue bars) with examples of planetary systems: (1) the giant planet orbits outside the HZ, (2) the giant planet orbits inside the HZ, and (3) the giant planet orbits inside the inner edge of the HZ. Color images available online at www.liebertonline.com/ast.

different HZ (see Fig. 14) that can be defined from the dynamical point of view.

HD41004AB can be divided into two subsystems, with a projected distance of the two stellar components (a K1V and an M2V star) between 20 and 23 AU, according to the different observations. Both stars have a substellar companion: (i) a planet of $2.3 M_{\text{Jup}}$ orbiting HD41004A at a distance between 1.31 and 1.7 AU in a quite high eccentric motion (between 0.39 and 0.74) and (ii) a brown dwarf of more than $18 M_{\text{Jup}}$ that orbits HD41004B in about 1.328 days. Stability studies of terrestrial planets in this system have shown that the first orbital parameter set provides the possibility of long-term stable motion within the HZ, which is limited to the inner region of the HZ (up to 0.7 AU). Moreover, the eccentricities of the binary and the giant planet should not be too high (<0.3). The stability map shows that the HZ is fragmented into several stable stripes. This structure can be explained by MMRs with the detected giant planet—where the 4:1 MMR is near 0.52 AU, the 7:2 MMR is near 0.57 AU, the 3:1 MMR is near 0.63 AU, and the 8:3 MMR is near 0.68 AU (for details see Pilat-Lohinger and Funk, 2010).

The binary *gamma Cephei* consists of a K1 IV star (of 1.6 solar masses) and a M4 V star (of 0.4 solar masses). Stability studies of this system confirm the long-term stability of the detected planet. Since the giant planet moves within the HZ, only habitable Trojan-type planets or habitable moons can be expected in this planetary system.

The binary Gliese 86 consists of a K1V (0.7 solar masses) and a white dwarf (with a minimum mass of 0.55 solar masses) at about 21 AU (according to observations by Murgauer and Neuhäuser, 2005). Queloz *et al.* (2000) found a very close giant planet at 0.11 AU with an orbital period of less than 16 days. Due to the CORALIE measurements, a minimum mass of $4 M_{\text{Jup}}$ was determined. As the detected gas giant moves at 0.11 AU, its gravitational influence on the HZ cannot be strong. Stability studies have shown the HZ of Gliese86 to be in a very stable state up to an eccentricity of the binary of 0.7. [Details can be found in Pilat-Lohinger and Funk (2010)].

8. Conclusions

If, in the near future, terrestrial exoplanets are discovered in the HZs of known EPS, it is not impossible, from a dynamical point of view, that such planets are in fact orbiting within the favorable region where life may have originated in systems we have already observed. Transit observations from space² over longer time periods, along with the necessary radial velocity measurements from the ground, will provide this very crucial information, which will not only impact the scientific community but all of civilization as well.

Acknowledgments

R.D. (project P18930-N16), E.P.-L. (project P19569-N16), and B.F. (Erwin Schrödinger grant J2892-N16) wish to acknowledge support by the Austrian science foundation FWF. R.S. wishes to acknowledge the support of the Österreichische Forschungsgesellschaft (project MOEL 309).

Abbreviations

ASR, apsidal secular resonance; EPS, exoplanetary systems; MEGNO, mean exponential growth factor of nearby orbits; MMR, mean motion resonance.

References

- Asghari, N., Broeg, C., Carone, L., Casas-Miranda, R., Castro Palacio, J.C., Csillik, I., Dvorak, R., Freistetter, F., Hadjivantsides, G., Hussmann, H., Khramova, A., Khristoforova, M., Khromova, I., Kitiashvili, I., Kozłowski, S., Laakso, T., Łaczkowski, T., Lytvinnenko, D., Miloni, O., Morishima, R., Moro-Martin, A., Paksyutov, V., Pal, A., Patidar, V., Pecnik, B., Peles, O., Pyo, J., Quinn, T., Rodriguez, A., Romano, C., Saikia, E., Stadel, J., Thiel, M., Todorovic, N., Veras, D., Vieira Neto, E., Vilagi, J., von Bloh, W., Zechner, R., and Zhuchkova, E. (2004) Stability of terrestrial planets in the habitable zone of Gl 777 A, HD 72659, Gl 614, 47 Uma and HD 4208. *Astron. Astrophys.* 426:353–365.
- Barge, P., Baglin, A., Auvergne, M., and the CoRoT team. (2008) CoRoT: pioneer space mission for exoplanet transit search. In *Exoplanets: Detection, Formation & Dynamics. Proceedings of the International Astronomical Union, IAU Symposium Vol. 249*, edited by Y.S. Sun, S. Ferraz-Mello, and J.L. Zhou, International Astronomical Union, Paris, pp 3–16.
- Beaugé, C., Ferraz-Mello, S., and Michtchenko, T.A. (2008) In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 1–26.
- Bois, E., Kiseleva-Eggleton, L., Rambaux, N., and Pilat-Lohinger, E. (2003) Conditions of dynamical stability for the HD 160691 planetary system. *Astrophys. J.* 598:1312–1320.
- Butler, R. and Marcy, G. (1996) A planet orbiting 47 Ursae Majoris. *The Astrophysical Journal Letters* 464:L153
- Butler, R., Marcy, G., Vogt, S.S., Fischer, D.A., Henry, G.W., Laughlin, G., and Wright, J.T. (2003) Seven new Keck planets orbiting G and K Dwarfs. *Astrophys. J.* 582:455–466.
- Chiang, E.I. and Murray, N. (2002) Eccentricity excitation and apsidal resonance capture in the planetary system Upsilon Andromedae. *Astrophys. J.* 576:473–477.
- Cincotta, P.M. and Simó, C. (2000) Simple tools to study global dynamics in non-axisymmetric galactic potentials—I. *Astronomy & Astrophysics Supplement* 147:205–228.
- Cincotta, P.M., Giordano, C.M., and Simó, C. (2003) Phase space structure of multi-dimensional systems by means of the mean exponential growth factor of nearby orbits. *Physica D* 182:151–178.
- Dvorak, R. (1984) Numerical experiments on planetary orbits in double stars. *Celestial Mechanics* 34:369–378.
- Dvorak, R. (2008) *Extrasolar Planets, Formation, Detection and Dynamics*, Wiley-VCH, Berlin.
- Dvorak, R. and Pilat-Lohinger, E. (2008) Terrestrial planets in extrasolar planetary systems. In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 27–50.
- Dvorak, R., Froeschle, C., and Froeschle, Ch. (1989) Stability of outer planetary orbits (P-types) in binaries. *Astron. Astrophys.* 226:335–342.
- Dvorak, R., Pilat-Lohinger, E., Funk, B., and Freistetter, F. (2003) A study of the stable regions in the planetary system HD 74156—can it host Earth-like planets in habitable zones? *Astronomy & Astrophysics Letters* 410:L13–L16.
- Érdi, B., Dvorak, R., Sándor, Zs., Pilat-Lohinger, E., and Funk, B. (2004) The dynamical structure of the habitable zone in the HD 38529, HD 168443 and HD 169830 systems. *Mon. Not. R. Astron. Soc.* 351:1043–1048.

²For details we refer to Rauer and Erikson (2008).

- Ferraz-Mello, S., Michtchenko, T.A., and Beaugé, C. (2005) The orbits of the extrasolar planets HD 82943c and b. *Astrophys. J.* 621:473–481.
- Froeschlé, C., Lega, E., and Gonczi, R. (1997) Fast Lyapunov indicators. Application to asteroidal motion. *Celestial Mechanics and Dynamical Astronomy* 67:41–62.
- Gayon, J. and Bois, E. (2008) Retrograde resonances in compact multi-planetary systems: a feasible stabilizing mechanism. In *Exoplanets: Detection, Formation & Dynamics. Proceedings of the International Astronomical Union, IAU Symposium Vol. 249*, edited by Y.S. Sun, S. Ferraz-Mello, and J.L. Zhou, International Astronomical Union, Paris, pp 511–516.
- Gozdziewski, K., Bois, E., Maciejewski, A.J., and Kiseleva-Eggleton, L. (2001) Global dynamics of planetary systems with the MEGNO criterion. *Astron. Astrophys.* 378:569–586.
- Gozdziewski, K., Bois, E., and Maciejewski, A.J. (2002) Global dynamics of the Gliese 876 planetary system. *Mon. Not. R. Astron. Soc.* 332:839–855.
- Hadjidemetriou, J.D. (2002) Resonant periodic motion and the stability of extrasolar planetary systems. *Celestial Mechanics and Dynamical Astronomy* 83:141–154.
- Holman, M.J. and Wiegert, P.A. (1999) Long-term stability of planets in binary systems. *Astrophys. J.* 117:621–628.
- Ji, J., Liu, L., Kinoshita, H., Zhou, J., Nakai, H., and Li, G. (2003) The librating companions in HD 37124, HD 12661, HD 82943, 47 Ursae Majoris, and GJ 876: alignment or antialignment? *The Astrophysical Journal Letters* 591:L57–L60.
- Kaltenegger, L. and Selsis, F. (2007) Biomarkers set in context. In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 79–98.
- Kasting, J.F., Whitmire, D.P., and Reynolds, R.T. (1993) Habitable zones around main sequence stars. *Icarus* 101:108–128.
- Kiseleva-Eggleton, L. and Bois, E. (2001) Effects of perturbing forces on the orbital stability of planetary systems. *The Astrophysical Journal Letters* 553:L73–L76.
- Kiseleva-Eggleton, L., Bois, E., Rambaux, N., Dvorak, R., and Rivera, E.J. (2002a) On the dynamical state of new multi-planet systems [24.04]. In *201st AAS Meeting. Bulletin of the American Astronomical and Astrophysical Society* 34:1144.
- Kiseleva-Eggleton, L., Bois, E., Rambaux, N., and Dvorak, R. (2002b) Global dynamics and stability limits for planetary systems around HD 12661, HD 38529, HD 37124, and HD 160691. *The Astrophysical Journal Letters* 578:L145–L148.
- Kiseleva-Eggleton, L., Bois, E., Guiderdoni, B., Dauphole, B., Rambaux, N., Gozdziewski, K., and Maciejewski, A.J. (2003) A new look at the dynamical properties of systems with multiple planets. In *Scientific Frontiers in Research on Extrasolar Planets*, edited by D. Deming and S. Seager, ASP Conference Series Vol. 294, Astronomical Society of the Pacific, San Francisco, pp 193–196.
- Kley, W., Peitz, J., and Bryden, G. (2004) Evolution of planetary systems in resonance. *Astron. Astrophys.* 414:735–747.
- Lammer, H., Khodachenko, M.L., Lichtenegger, H., and Kulikov, Y.N. (2008) Impact of stellar activity on the evolution of planetary atmospheres and habitability. In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 127–150.
- Laskar, J. (1990) The chaotic motion of the Solar System—a numerical estimate of the size of the chaotic zones. *Icarus* 88:266–291.
- Laskar, J. (1998) A numerical experiment on the chaotic behaviour of the Solar System. *Nature* 338:237–238.
- Laskar, J., Quinn, T., and Tremaine, S. (1992) Confirmation of resonant structure in the Solar System. *Icarus* 95:148–152.
- Laughlin, G. and Chambers, J.E. (2001) Short-term dynamical interactions among extrasolar planets. *The Astrophysical Journal Letters* 551:L109–L113.
- Laughlin, G. and Chambers, J.E. (2002) Extrasolar Trojans: the viability and detectability of planets in the 1:1 resonance. *Astrophys. J.* 124:592–600.
- Lee, M.H. and Peale, S.J. (2002) Dynamics and origin of the 2:1 orbital resonances of the GJ 876 planets. *Astrophys. J.* 567:596–609.
- Lee, M.H. and Peale, S.J. (2003) Secular evolution of hierarchical planetary systems. *Astrophys. J.* 592:1201–1216.
- Menou, K. and Tabachnik, S. (2003) Dynamical habitability of known extrasolar planetary systems. *Astrophys. J.* 583:473–488.
- Michtchenko, T.A., Ferraz-Mello, S., and Béauge, C. (2008) Dynamics of the extrasolar planetary systems. In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 151–178.
- Mugrauer, M. and Neuhauser, R. (2005) Gl86B: a white dwarf orbits an exoplanet host star. *Mon. Not. R. Astron. Soc.* 361: L15–L19.
- Naef, D., Mayor, M., Korzennik, S.G., Queloz, D., Udry, S., Nisenson, P., Noyes, R.W., Brown, T.M., Beuzit, J.L., Perrier, C., and Sivan, J.P. (2003) The ELODIE survey for northern extra-solar planets. II. A jovian planet on a long-period orbit around GJ 777 A. *Astron. Astrophys.* 410:1051–1054.
- Naef, D., Mayor, M., Beuzit, J.L., Perrier, C., Queloz, D., Sivan, J.P., and Udry, S. (2004) The ELODIE survey for northern extra-solar planets. III. Three planetary candidates detected with ELODIE. *Astron. Astrophys.* 414:351–359.
- Pilat-Lohinger, E. and Dvorak, R. (2008) Planets in double stars. In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 179–206.
- Pilat-Lohinger, E. and Funk, B. (2010) Dynamical stability of extra-solar planets. *Lecture Notes in Physics* 790:481–510.
- Pilat-Lohinger, E., Funk, B., and Dvorak, R. (2003) Stability limits in double stars. A study of inclined planetary orbits. *Astron. Astrophys.* 400:1085–1094.
- Queloz, D., Mayor, M., Weber, L., Blicha, A., Burnet, M., Confino, B., Naef, D., Pepe, F., Santos, N., and Udry, S. (2000) The CORALIE survey for southern extra-solar planets. I. A planet orbiting the star Gliese 86. *Astron. Astrophys.* 354:99–102.
- Rauer, H. and Erikson, A. (2008) The transit method. In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 207–240.
- Raymond, S.N. (2006) The search for other Earths: limits on the giant planet orbits that allow habitable terrestrial planets to form. *The Astrophysical Journal Letters* 643:L131–L134.
- Raymond, S.N. and Barnes, R. (2005) Predicting planets in known extrasolar planetary systems. II. Testing for Saturn mass planets. *Astrophys. J.* 619:549–557.
- Raymond, S.N., Quinn, T., and Lunine, J.I. (2004) Making other Earths: dynamical simulations of terrestrial planet formation and water delivery. *Icarus* 168:1–17.
- Raymond, S.N., Barnes, R., and Kaib, N.A. (2006) Predicting planets in known extrasolar planetary systems. III. Forming terrestrial planets. *Astrophys. J.* 644:1223–1231.
- Sándor, Zs., Süli, Á., Érdi, B., Pilat-Lohinger, E., and Dvorak, R. (2007) A stability catalogue of the habitable zones in extrasolar planetary systems. *Mon. Not. R. Astron. Soc.* 375:1495–1502.
- Schwarz, R., Dvorak, R., Süli, Á., and Érdi, B. (2007) Survey of the stability region of hypothetical habitable Trojan planets. *Astron. Astrophys.* 474:1023–1029.
- Vogt, S.S., Butler, R.P., Marcy, G.W., Fischer, D.A., Pourbaix, D., Apps, K., and Laughlin, G. (2002) Ten low-mass companions

- from the Keck precision velocity survey. *Astrophys. J.* 568:352–362.
- von Bloh, W., Bounama, C., and Franck, S (2008) Habitable zones in extrasolar planetary systems. In *Extrasolar Planets: Formation, Detection and Dynamics*, edited by R. Dvorak, Wiley-VCH, Berlin, pp 257–283.
- Zhou, J.-L. and Sun, Y.-S. (2003) Occurrence and stability of apsidal resonance in multiple planetary systems. *Astrophys. J.* 598:1290–1300.

Address correspondence to:
Rudolf Dvorak
Institute for Astronomy
University of Vienna
Vienna
Austria

E-mail: dvorak@astro.univie.ac.at

